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PROVISIONAL APPLICATION FOR PATENT COVER SHEET

This is a request for filing a PROVISIONAL APPLICATION FOR PATENT under 37 CFR 1.53(c).

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☐ *Additional inventors are being named on the ____ separately numbered sheets attached hereto*

TITLE OF THE INVENTION (280 characters max)

AN ADAPTIVE CONTROL METHOD FOR ACQUIRING IMPROVED 4D THORACIC CT SCANS

Direct all correspondence to: **CORRESPONDENCE ADDRESS**

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ENCLOSED APPLICATION PARTS *(check all that apply)*

☒ Specification *Number of Pages* 8 ☐ CD(s), Number

☒ Drawing(s) *Number of* ~~Sheets~~ Figures 4 ☐ Other (specify)

☐ Application Data Sheet. See 37 CFR 1.76

METHOD OF PAYMENT OF FILING FEES FOR THIS PROVISIONAL APPLICATION FOR PATENT *(check one)*

☒ Applicant claims small entity status. See 37 CFR 1.27.
☒ A check or money order is enclosed to cover the filing fees
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FILING FEE AMOUNT ($) **$80.00**

The invention was made by an agency of the United States Government or under a contract with an agency of the United States Government.

☒ No.
☐ Yes, the name of the U.S. Government agency and the Government contract number are: ____________

Respectfully submitted,

SIGNATURE Ruth Tyler-Cross

Date 4-8-04

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Docket Number: 02940350PR

USE ONLY FOR FILING A PROVISIONAL APPLICATION FOR PATENT

An Adaptive Control Method for Acquiring Improved 4D Thoracic CT Scans

Abstract

Four-dimensional computed tomography (4DCT) acquisition methods that explicitly account for respiratory motion have been recently developed in academic and commercial settings. 4DCT is generally acquired either by sinogram or image sorting based on a postacquisition procedure using external respiration signals. The patient's ability to maintain reproducible respiratory signals is the limiting factor during 4DCT. Methods of breathing coaching, e.g. audiovisual biofeedback can improve respiration reproducibility, however significant variations remain which cause artifacts in the 4DCT scan. To reduce these artifacts, and subsequent effects during radiotherapy planning and delivery, a method for improved 4DCT image acquisition has been developed that relies on adaptive control during data acquisition. The respiration signal and CT data acquisition are linked, such that 'bad' data from erratic breathing cycles that cause artifacts are not acquired by pausing CT acquisition until steady state respiration is resumed. A proof-of-principal application of the adaptive control method to an existing respiration signal acquired during 4DCT demonstrates the potential of this method to reduce artifacts currently found in 4DCT scans. Though 4DCT methods accounting for respiratory motion are being developed in radiation oncology departments, there is potentially a significant widespread role of 4DCT in diagnostic radiology for pulmonary function tests. Limiting the widespread application of 4DCT is the utility of current passive acquisition techniques to account for the variations in patient's respiratory signals. Active 4DCT acquisition processes, such as the adaptive control method, will potentially allow the general use of 4DCT.

1. Introduction

Respiratory motion degrades anatomic position reproducibility during imaging [1-11] necessitates larger margins during radiotherapy planning[12, 13], and causes errors during radiation delivery[14-19]. Clinically significant lung tumor motion cannot be predicted by any known clinical parameters [20], suggesting that tumor motion must be explicitly determined for each patient. In fact, recent EORTC guidelines (Senan *et al* Rad Onc In press) state *An assessment of 3D tumour mobility is essential for treatment planning and delivery in lung cancer.* Methods to account for respiratory motion during CT imaging include breath-hold, respiratory gating, and four-dimensional (4D) CT, the subject of the current research. 4D thoracic CT images accounting for respiratory motion have successfully been acquired using single slice scanners [9, 10], however, the authors of these works acknowledge the temporal and spatial limitations of 4D acquisition with current single slice technology. Multislice 4D CT scans have been acquired using an axial/cine method at Washington University [21], Memorial Sloan Kettering Cancer Center [22], and Massachusetts General Hospital[23-25], and using a helical method at the MD Anderson Cancer Center[26]. 4D cone-beam CT scans have been acquired using a benchtop system by Taguchi[27] as well as clinically at the Netherlands Cancer Institute[28].

4D thoracic CT techniques build on those existing for cardiac imaging, in which the cardiac signal is input to the CT scanner during the sinogram evolution, from which image reconstruction at several cardiac phases can occur [29]. However, a factor limiting the success of 4D thoracic CT is the irregularity of respiratory cycles in both displacement and cycle-to-cycle period. Irregularity manifests itself as imaging artifacts, leading to anatomical mismatches (see e.g. Fig 10c and Fig. 10d of [26]), or insufficient acquisition of projection data to reconstruct a full image (see e.g. Fig. 9 of [26]). To reduce this irregularity, audio and audio-visual breathing training methods have been applied to try to improve the quality of 4D thoracic CT data [26, 30, 31], however, even with audio-visual breathing training respiration irregularities remain, as shown in Figure 1. An approach complimentary to breathing training to improve respiration reproducibility is to recognize irregularities and modify the scan acquisition itself. The scan acquisition could be modified such that projection data from irregular breathing cycles be ignored or not

acquired at all, and sufficient projection data from regular respiration cycles is acquired to obtain a 4D thoracic CT with minimum artifacts.

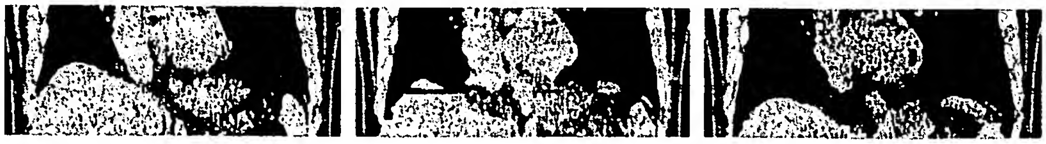


Figure 1. Coronal CT scans of a 4D CT at three respiratory phases for a patient undergoing audio-visual breathing training. Note the artifact near the dome of the right diaphragm in the central image.

The use of 4D thoracic CT has been developed for and applied to radiation oncology patients. However, high quality 4D CT data, along with accurate deformable image registration algorithms to automate analysis of this data, could play and important role in the analysis of lung function for a variety of pulmonary diseases. The changes in local density of the lung as a function of respiration could be automatically detected and the abnormal regions displayed, leading to faster diagnosis.

Thus the aim of this research was to develop an adaptive control algorithm that takes as input the respiration signal and based on this input controls the CT scanner during the acquisition of a 4D thoracic CT scan to reduce the magnitude of artifacts introduced by irregular respiration.

2. Method

The adaptive control method described below requires a respiratory monitoring system to be tightly integrated into the CT scan control, and interactive control of both the CT acquisition and couch motion. The method comprises of several pre-scan steps, the CT data acquisition itself, and post-acquisition processing.

Box 1 of Figure 2 requires breathing training. Though this step is not required, based on as yet unpublished data collected on lung cancer patients at VCU, the use of audio-visual breathing training strongly improves respiratory reproducibility. Box 2 of Figure 2 gives time for the patient to fall into a reasonably regular breathing pattern. Once breathing is

regular, Box 3 of Figure 2 learns the respiration pattern of an average breathing cycle. Spatial and temporal tolerances for which data acquisition will//will not occur are given in Box 4 of Figure 2. Due to the variation within breathing cycles, a pre-set lower limit can be calculated based on the respiration patterns of the data used to lean the average breathing cycle. In Box 2 of Figure 2 the reconstruction criteria are input. This could be a single scan acquired at a given point in the breathing cycle, e.g. end inhale, or multiple scans to be acquired at several points within the respiratory cycle.

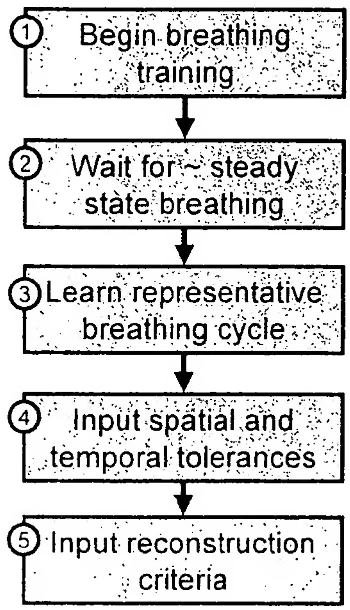


Figure 2. The pre-scan procedures.

Once the pre-scan procedures are complete, the scan itself can occur. A flowchart of the adaptive control method for 4D CT is given in Figure 3. The tolerances set in box 4 of Figure 2 are used to determine whether to pause data acquisition, if the current respiratory trace is outside the spatial or temporal tolerance, or continue if the tolerances are met. The second decision box in Figure 3, determining if sufficient data has been acquired for reconstruction, is dependent on the input reconstruction criteria input in box 5 of Figure 2. A tally is required to ensure that the entire geometry scanned has had sufficient data acquisition to ensure reconstruction without missing data can occur.

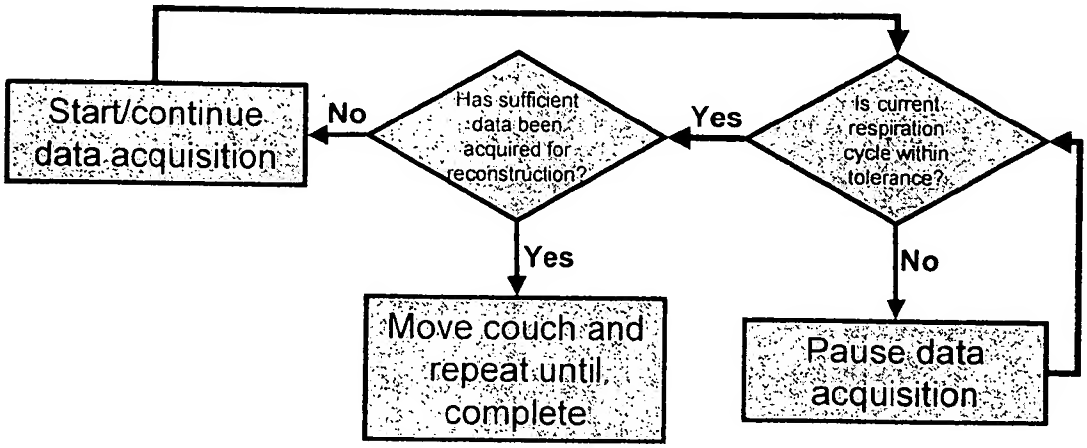
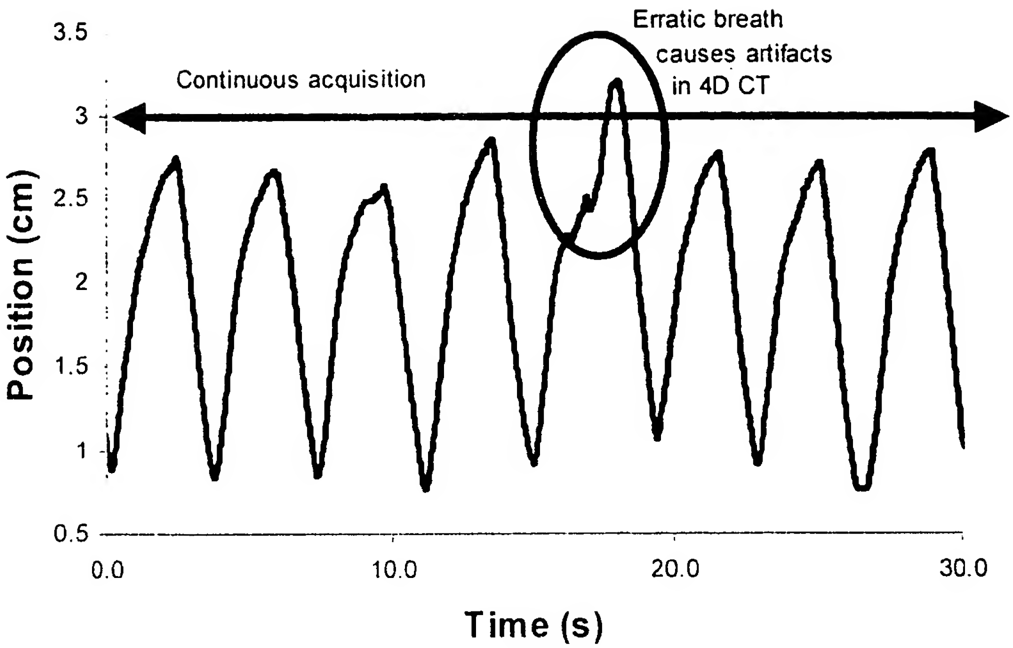


Figure 3. The adaptive CT control during CT data acquisition.

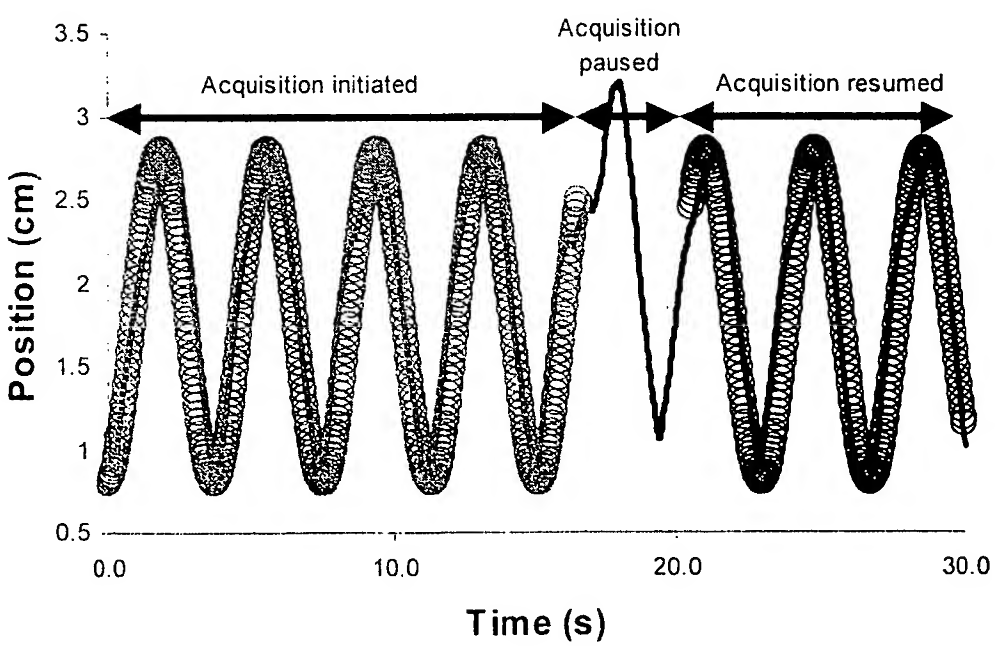
After acquisition, image reconstruction can automatically occur based on the requirements input in box 5 of Figure 2.

4. Results

A respiration signal taken during 4D CT with audio-visual biofeedback is shown in Figure 4. The respiration signal is very regular apart from a single erratic respiration cycle which, under continuous acquisition causes artifacts in the 4D CT image. Adaptive CT acquisition pauses the acquisition once the irregular respiration signal is detected, and restarts data acquisition once steady-state breathing is resumed.



(a)



(b)

Figure 4. (a) An example of very regular respiration signal (acquired during 4D CT with audio-visual biofeedback) apart from a single erratic respiration cycle which, under continuous acquisition causes artifacts in the 4D CT image. (b) An example of the adaptive CT acquisition pausing the acquisition once the irregular respiration signal is detected, and restarting data acquisition once steady-state breathing is resumed.

5. Discussion

This article describes an adaptive control algorithm that takes as input the respiration signal and based on this input controls the CT scanner during the acquisition of a 4D thoracic CT scan to reduce the magnitude of artifacts introduced by irregular respiration. The implementation of such an algorithm would require a major engineering effort by a CT manufacturer and is beyond the capabilities our institution, and thus the algorithm will remain 'on paper' until such a major effort is performed. Time will tell if the adaptive control algorithm is (a) feasible and (b) useful for 4D thoracic CT.

The method described above is flexible enough to allow both sequential axial and helical 4D CT acquisition, however the axial approach is probably the easiest to implement.

A logical extension of this technique is to only acquire data during the parts of the respiratory cycle when reconstructed cans are requested. For example, if a CT scan at end-inhale is requested, then data at other parts of the respiratory cycle need not be acquired.

The use of 4D thoracic CT has been developed for and applied to radiation oncology patients. However, high quality 4D CT data, along with accurate deformable image registration algorithms to automate analysis of this data, could play and important role in the analysis of lung function for a variety of pulmonary diseases. The changes in local density of the lung as a function of respiration could be automatically detected and the abnormal regions displayed, leading to faster diagnosis.

Improved 4D CT will also help improve PET/CT that suffers from motion artifacts.

Though the efforts here have been directed towards respiratory motion, other motion such as skeletal and gastro-intestinal motion could also be used for adaptive control, provided the appropriate monitoring system can be integrated with the CT control system.

5. References

1. Keall PJ, Kini VR, Vedam SS. *et al.* Potential radiotherapy improvements with respiratory gating. *Australas Phys Eng Sci Med* 2002;25:1-6.
2. Shimizu S, Shirato H, Ogura S, *et al.* Detection of lung tumor movement in real-time tumor-tracking radiotherapy. *Int J Radiat Oncol Biol Phys* 2001;51:304-310.
3. Shepp LA, Hilal SK, Schulz RA. The tuning fork artifact in computerized tomography. *Comput. Graph Image Processing* 1979;10:246-255.
4. Tarver RD, Conces DJ, Godwin JD. Motion artifacts on CT simulate bronchiectasis. *Am J Roentgenol.* 1988,151:1117-1119.
5. Ritchie CJ, Hseih J, Gard MF, *et al.* Predictive respiratory gating: A new method to reduce motion artifacts on CT scans. *Radiology* 1994;190:847-852.
6. Mayo JR, Müller NL, Henkelman RM. The double-fissure sign: a motion artifact on thin-section CT scans. *Radiology* 1987;165:580-581.
7. Ritchie CJ, Godwin JD, Crawford CR. *et al.* Minimum scan speeds for suppresion of motion artifacts in CT. *Radiology* 1992;185:37-42.
8. Shimizu S, Shirato H, Kagei K. *et al.* Impact of respiratory movement on the computed tomographic images of small lung tumors in three-dimensional (3D) radiotherapy. *Int J Radiat Oncol Biol Phys* 2000;46:1127-1133.
9. Vedam SS, Keall PJ, Kini VR. *et al.* Acquiring a four-dimensional computed tomography dataset using an external respiratory signal. *Phys Med Biol* 2003;48:45-62.
10. Ford EC, Mageras GS, Yorke E. *et al.* Respiration-correlated spiral CT: a method of measuring respiratory-induced anatomic motion for radiation treatment planning. *Med Phys* 2003;30:88-97.
11. Balter JM, Ten Haken RK, Lawrence TS. *et al.* Uncertainties in CT-based radiation therapy treatment planning associated with patient breathing. *Int J Radiat Oncol Biol Phys* 1996;36:167-174.
12. ICRU. ICRU Report 50. Prescribing, recording and reporting photon beam therapy. Bethesda, MD: International Commission on Radiation Units and Measurements; 1993.
13. ICRU. ICRU Report 62. Prescribing, Recording and Reporting Photon Beam Therapy (Supplement to ICRU Report 50). Bethesda, MD: International Commission on Radiation Units and Measurements; 1999.
14. Yu CX, Jaffray DA, Wong JW. The effects of intra-fraction organ motion on the delivery of dynamic intensity modulation. *Phys. Med. Biol.* 1998;43:91-104.
15. Bortfeld T, Jokivarsi K, Goitein M. *et al.* Effects of intra-fraction motion on IMRT dose delivery: statistical analysis and simulation. *Phys Med Biol* 2002;47:2203-2220.
16. George R, Keall PJ, Kini VR. *et al.* Quantifying the effect of intrafraction motion during breast IMRT planning and dose delivery. *Med Phys* 2003;30:552-562.
17. Keall PJ, Kini V, Vedam SS. *et al.* Motion Adaptive X-ray Therapy: A feasibility study. *Phys. Med. Biol.* 2001;46:1-10.
18. Chui CS, Yorke E, Hong L. The effects of intra-fraction organ motion on the delivery of intensity-modulated field with a multileaf collimator. *Med Phys* 2003;30:1736-1746.
19. Jiang SB, Pope C, Al Jarrah KM. *et al.* An experimental investigation on intra-fractional organ motion effects in lung IMRT treatments. *Phys Med Biol* 2003;48:1773-1784.
20. Stevens CW, Munden RF, Forster KM. *et al.* Respiratory-driven lung tumor motion is independent of tumor size, tumor location, and pulmonary function. *Int J Radiat Oncol Biol Phys* 2001;51:62-68.
21. Low DA, Nystrom M, Kalinin E. *et al.* A method for the reconstruction of four-dimensional synchronized CT scans acquired during free breathing. *Med Phys* 2003;30:1254-1263.
22. Mageras GS. Respiration correlated CT techniques for gated treatment of lung cancer. *Radiotherapy and Oncology* 2002;64:75
23. Rietzel E, Doppke K, Pan T. *et al.* 4D computer tomography for radiation therapy (abstract). *Med Phys* 2003;30:1365-1366
24. Rietzel E, Chen GT, Doppke KP. *et al.* 4D computed tomography for treatment planning. *Int J Radiat Oncol Biol Phys* 2003;57:S232-233.
25. Pan T. etal. 4D-CT imaging of a volume influenced by respiratory motion on multi-slice CT. *Med Phys: To update when available on Pubmed* 2004.
26. Keall PJ, Starkschall G, Shukla H. *et al.* Acquiring 4D Thoracic CT Scans using a Multislice Helical Method. *Phys Med Biol* 2003;Submitted.
27. Taguchi K. Temporal resolution and the evaluation of candidate algorithms for four-dimensional CT. *Med Phys* 2003;30:640-650.
28. Sonke J, Remeijer P, van Herk M. Respiration-correlated cone beam CT: Obtaining a four-dimensional data set (abstract). *Med Phys* 2003;30:1415.
29. Grass M, Manzke R, Nielsen T, *et al.* Helical cardiac cone beam reconstruction using retrospective ECG gating. *Phys Med Biol* 2003;48:3069-3084.
30. Vedam SS, Kini VR, Keall PJ. *et al.* Quantifying the predictability of diaphragm motion during respiration with a noninvasive external marker. *Med Phys* 2003;30:505-513.
31. Kini VR, Vedam SS, Keall PJ, *et al.* Patient training in respiratory-gated radiotherapy. *Med Dosim* 2003;28:7-11.